Color Sextet Scalars at the CERN Large Hadron Collider

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Abstract

Taking a phenomenological approach, we study a color sextet scalar at the LHC. We focus on the QCD production of a color sextet pair $\Phi_6 \bar{\Phi}_6$ through gg fusion and $q\bar{q}$ annihilation. Its unique coupling to $\bar{\psi}^c \psi$ allows the color sextet scalar to decay into same-sign diquark states, such as $\Phi_6 \to tt/tt^*$. We propose a new reconstruction in the multijet plus same sign dilepton with missing transverse energy samples ($bb + \ell^\pm \ell^\pm + \not{E}_T + Nj$, $N \geq 6$) to search for on-shell $tt\bar{t}\bar{t}$ final states from sextet scalar pair production. Thanks to the large QCD production, the search covers the sextet mass range up to 1 TeV for 100 fb^{-1} integrated luminosity.

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arXiv:0811.2105v2 [hep-ph] 7 Feb 2009

I. INTRODUCTION

The Large Hadron Collider (LHC) at CERN will soon provide a great opportunity for exploring physics at the TeV scale. As a proton-proton collider with a total center-of-mass energy of 14 TeV, the LHC is truly a Quantum Chromodynamics (QCD) machine. We therefore wish to study color exotics, since any accessible new physics in the strong interaction sector will appear in the early stages of LHC operation. Many models of physics beyond the standard model (SM) naturally require the presence of color exotics, such as gluinos and squarks in supersymmetric extensions of standard model, KK-gluons and KK-quarks in extra dimensional models, or the top-prime in Little Higgs or twin Higgs models. All of these are either quark or gluon partners which belong to the fundamental and adjoint representations of the QCD gauge group $SU(3)_C$ respectively. It is natural to consider colored particles in other representations; in this paper, we focus on a scalar which is in the sextet(6) representation of $SU(3)_C$. Color sextet particles have been widely discussed in nuclear physics as diquark condensate states; in the SSC era, sextet quarks were discussed in [1].

Color sextet scalars are naturally present in partial unification [2], grand unification [3] and composite models; in some cases they may be present around the weak scale. For instance, in a supersymmetric Pati-Salam $SU(2)_R \times SU(2)_L \times SU(4)_C$ model, light color sextet scalars can be realized around the weak scale, even though the scale of $SU(2)_R \times SU(4)_C$ symmetry breaking is around 10^{10} GeV due to existence of accidental symmetries with the masses of color sextet Higgs arising only through high dimension operators [4, 5]. In this case, the introduction of a color sextet Higgs will not lead to proton decay but only to neutron-anti-neutron $(n - \bar{n})$ oscillation and is fully compatible with present limits [4, 5]. In a similar framework, light color sextet scalars also help in Post-Sphaleron baryogenesis [7]. In this paper, however, we will take a purely phenomenological approach toward the sextet scalar without assuming any model a priori.

Among all the color exotics, the color sextet scalar is unique in its coupling to quarks. In group theory language, the color sextet lies in $3 \otimes 3 = 6 \oplus \bar{3}$ as a symmetric 2$^{\text{nd}}$ rank tensor under $SU(3)_C$. The Lorentz structure for this scalar coupling to quarks is given by $\psi^T C^{-1} \psi \phi$, where ψ is a Dirac spinor and ϕ is the scalar. Under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, the sextet scalar can be Δ_6, a $SU(2)_L$ adjoint $(6, 3, 1/3)$; Φ_6, a $SU(2)_L$

singlet $(6, 1, 4/3)$; ϕ_6, a $SU(2)_L$ singlet $(6, 1, -2/3)$; or δ_6, a $SU(2)_L$ singlet $(6, 1, +1/3)$. The color sextet scalars are also charged under the global baryon symmetry $U(1)_B$ and the electromagnetic symmetry $U(1)_{\rm EM}$. To avoid breaking $U(1)_{\rm EM}$, these scalar fields should not develop a non-zero vacuum expectation value. This condition removes any possibility of $n - \bar{n}$ oscillation in the minimal model involving color sextet scalars. We may write down the flavor independent Lagrangian of such a minimal model by only considering SM gauge invariants and keeping $U(1)_{\rm EM}$ unbroken,

$$
\begin{aligned}
\mathcal{L} = {} & \text{Tr}[(D_\mu \Delta_6)^\dagger (D^\mu \Delta_6)] - M_\Delta^2 \text{Tr}[\Delta_6^\dagger \Delta_6] + f_\Delta Q_L^T C^{-1} \tau_2 \Delta_6^\dagger Q_L \\
& + (D_\mu \Phi_6)^\dagger (D^\mu \Phi_6) - M_\Phi^2 \Phi_6^\dagger \Phi_6 + f_\Phi u_R^T C^{-1} u_R \Phi_6^\dagger \\
& + (D_\mu \phi_6)^\dagger (D^\mu \phi_6) - M_\phi^2 \phi_6^\dagger \phi_6 + f_\phi d_R^T C^{-1} d_R \phi_6^\dagger \\
& + (D_\mu \delta_6)^\dagger (D^\mu \delta_6) - M_{\delta_6}^2 \delta_6^\dagger \delta_6 + f_\delta d_R^T C^{-1} u_R \delta_6^\dagger \\
& - \lambda_\Delta (\text{Tr}[\Delta_6^\dagger \Delta_6])^2 - \lambda_\Phi (\Phi_6^\dagger \Phi_6)^2 - \lambda_\phi (\phi_6^\dagger \phi_6)^2 - \lambda_\delta (\delta_6^\dagger \delta_6)^2 \\
& - \lambda_\Delta' \text{Tr}[\Delta_6^\dagger \Delta_6 \Delta_6^\dagger \Delta_6] - \text{Tr}[\Delta_6^\dagger \Delta_6](\lambda_1 \Phi_6^\dagger \Phi_6 + \lambda_2 \phi_6^\dagger \phi_6 + \lambda_3 \delta_6^\dagger \delta_6) \\
& - \lambda_4 \Phi_6^\dagger \Phi_6 \phi_6^\dagger \phi_6 - \lambda_5 \Phi_6^\dagger \Phi_6 \delta_6^\dagger \delta_6 - \lambda_6 \phi_6^\dagger \phi_6 \delta_6^\dagger \delta_6 \ ,
\end{aligned}
\tag{1}
$$

where the QCD covariant derivative is defined as $D_\mu = \partial_\mu - i g_s G_\mu^a T_r^a$, and the T_r^a are the representation matrices for the sextet; M_i^2, λ_i and f_i are all positive-definite model parameters.

If we consider the $SU(2)_L$ adjoint sextet scalar Δ_6 , there will be three physical sextet scalar states that couple to up-type quark pairs, down-type quark pairs, and up-down type quark pairs. When the sextet scalar decays into light quark states, the existing search strategies for massive octet scalars or vectors [8] may be employed. Δ_6, Φ_6 and δ_6 may all contribute to the single top plus jet singal and $t\bar{t} + Nj$ signal from pair production. Here we consider the scenario in which a color sextet scalar decays into a top quark pair so that one can use the leptons from the top quark decay to determine the features of the sextet. Signature that contains multi-top final states has been discussed in the context of many new physics models as resonance decaying into top quarks or top composite[5, 6]. To illustrate this and simplify our search, our study will focus on the color sextet $SU(2)$ singlet scalar Φ_6 that only couples to righthanded up-type quarks.

II. DECAY OF THE COLOR SEXTET SCALAR

The decay of the Φ_6 depends on its mass, M_{Φ_6}, and its couplings to quarks, f_{ij} ($i,j = u,c,t$). To illustrate our reconstruction algorithm in the discussion of discovery, we consider the case where $M_{\Phi_6} > 350$ GeV and the Φ_6 decays into two onshell top quarks; other mass ranges are discussed in the conclusion section. Above threshold, the general expression for the decay partial widths of the sextet scalar are

$$\begin{aligned}
\Gamma_{ii} &= \frac{3}{16\pi}|f_{ii}|^2 M_{\Phi_6}\lambda^{1/2}(1, r_i^2, r_i^2)(1 - 4r_i^2) \\
\Gamma_{ij} &= \frac{3}{8\pi}|f_{ij}|^2 M_{\Phi_6}\lambda^{1/2}(1, r_i^2, r_j^2)(1 - r_i^2 - r_j^2)
\end{aligned} \tag{2}$$

where $\lambda(x, y, z) = (x - y - z)^2 - 4yz$ and $r_i = m_i/M_{\Phi_6}$.

By far, the most stringent bounds on these parameters come from $D^0 - \bar{D}^0$ mixing, to which Φ_6 would make a tree level contribution proportional to $f_{11}f_{22}/M_{\Phi_6}^2$. The off-diagonal coupling f_{ij} will contribute to flavor violation processes, for instance $D \to \pi\pi$ which is proportional to $f_{12}f_{11}/M_{\Phi_6}^2$. The current bounds require that

$$f_{11}f_{22} \lesssim 10^{-6}; f_{11}f_{12} \lesssim 10^{-2}, \tag{3}$$

for M_{Φ_6} of a few hundred GeV to TeV mass range [5, 9, 10]. One will also expect less stringent constraints from one loop process as $c \to u\gamma$. To escape from the bound, for acessible values of M_{Φ_6} we expect at least one of the couplings, f_{11} or f_{22}, to be negligible. However from our purely phenomenological perspective, we take the decay branching fraction BR($\Phi_6 \to tt$) to be a completely free parameter whose value may be determined at the LHC.

Because the sextet is a colored object, we need to consider the possibility of it hadronizing before decaying. For example, it may form a tetraquark-like bound state with $\bar{3}\bar{3}$, such as $\Phi_6\bar{u}\bar{u}$, $\Phi_6\bar{u}\bar{d}$, or $\Phi_6\bar{d}\bar{d}$, with charges $0, 1, 2$ respectively. If the total width is less than $\Lambda_{\rm QCD} \sim m_\pi$, then the colored object will hadronize before it decays. To determine the constraint imposed by the possibility of hadronization, in Fig. 1 we plot the contour for which decay width of Φ_6 is equal to $\Lambda_{\rm QCD}$ as a function of the couplings and the mass. Setting $f_{uu} = 0.001$, $f_{ut} = 0.001$, and eliminating any coupling to c, we see the possibility that a large portion of our parameter space will be protected from the risk of hadronization.
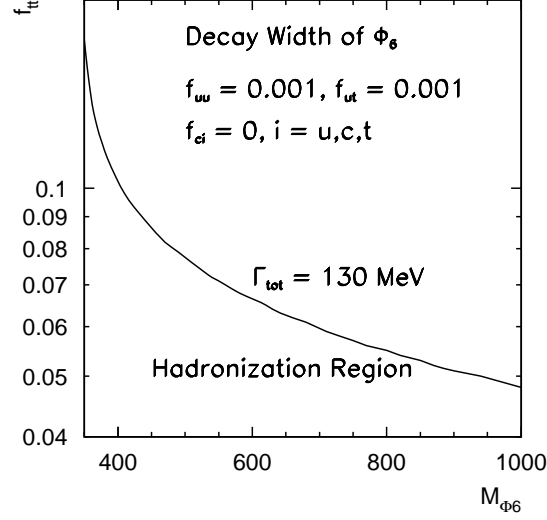
FIG. 1: Decay width contour for Φ_6 in the mass and coupling plane.

III.   PRODUCTION OF Φ_6

Because it carries color, Φ_6 can be produced directly through the QCD strong interaction at the LHC. The pair of $\bar{\Phi}_6\Phi_6$ is produced from gluon-gluon fusion or $q\bar{q}$ annihilation:

$$g(p_1) + g(p_2) \rightarrow \bar{\Phi}_6(k_1) + \Phi_6(k_2)$$

$$q(p_1) + \bar{q}(p_2) \rightarrow \bar{\Phi}_6(k_1) + \Phi_6(k_2). \tag{4}$$

The total production cross section depends only on the mass of Φ_6, since the vertex is just the strong coupling, g_s, as shown in Eq. (6). By comparison, the electroweak production of $\bar{\Phi}_6\Phi_6$ is small enough to be neglected in our search.

From the scalar QCD gauge interaction

$$(D_\mu\Phi_6)^\dagger(D^\mu\Phi_6), \quad \text{where} \quad D_\mu = \partial_\mu - ig_s G_\mu^a T^a, \tag{5}$$

one may obtain the Feynman rules

$$G_\mu^a \Phi_6 \bar{\Phi}_6 \ : \ ig_s(p_1 - p_2)_\mu T^a$$

$$G_\mu^a G_\nu^b \Phi_6 \bar{\Phi}_6 \ : \ -ig_s^2 g_{\mu\nu}(T^a T^b + T^b T^a). \tag{6}$$

The momenta are assigned according to $V_\mu S(p_1)\bar{S}(p_2)$ and all momenta are out-going. In group theory langauge, this is $6 \otimes \bar{6} = 27 \oplus 8 \oplus 1$.

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d_R	3	6	8
$C(R)$	1/2	5/2	3
$C_2(R)$	4/3	10/3	3

TABLE I: Normalization factor $C(R)$ and quadratic Casimir $C_2(R)$ for $d_R = 3, 6, 8$ under $SU(3)$.

The parton level cross sections for color a sextet pair production are given by

$$\sigma(q\bar{q} \to \bar{\Phi}_6 \Phi_6) = \pi C(3) C(R) \frac{d_8}{d_3^2} \frac{\alpha_s^2}{3s} \beta^3 = \frac{10\pi}{27s} \alpha_s^2 \beta^3 \tag{7}$$

and

$$\begin{aligned}
\sigma(gg \to \bar{\Phi}_6 \Phi_6) &= d_R C_2(R) \pi \frac{\alpha_s^2}{6s} \frac{1}{d_8^2} [3\beta(3 - 5\beta^2) - 12C_2(R)\beta(\beta^2 - 2) \\
&+ \ln|\frac{\beta + 1}{\beta - 1}|(6C_2(R)(\beta^4 - 1) - 9(\beta^2 - 1)^2] \\
&= \frac{5\pi}{96s} \alpha_s^2 [\beta(89 - 55\beta^2) + \ln|\frac{\beta + 1}{\beta - 1}|(11\beta^4 + 18\beta^2 - 29)] ,
\end{aligned} \tag{8}$$

where $\sqrt{s}$ is the total energy, $\beta = \sqrt{1 - 4M_{\Phi_6}^2/s}$ and R is 6 with the normalization factor C and Casimir C_2 satisfying

$$\text{Tr}[T_R^a T_R^b] = C(R)\delta^{ab} \quad \text{and} \quad T_R^a T_R^a = C_2(R)\mathbf{1}. \tag{9}$$

We list the values for different representations under $SU(3)$ as in Table I.

The QCD production cross sections for the color sextet scalar pair $\bar{\Phi}_6 \Phi_6$ at both LHC and Tevatron are plotted in Fig. 2 with factorization scale $\mu_F = M_{\Phi_6}$, renormalization scale $\mu_R = m_Z$ and the CTEQ6L [11] parton distribution function (PDF). The matrix elements in our calculations here and elsewhere are generated by SUSY-Madgraph [12] with modified color factors. For comparison, we also show the pair production cross sections for $SU(3)_C$ triplet and octet scalars at the LHC. As we can see, the total production cross section of the sextet scalar is similar to that of the octet scalar, but is about one order maginitude larger than that of the triplet scalar, which can be understood from values of C and C_2 for different reprensentations in Table I.

As discussed in the introduction, the color sextet scalar Φ_6 only couples to the righthanded up-type quark quark pair. Thus we may also have single production of a Φ_6 through
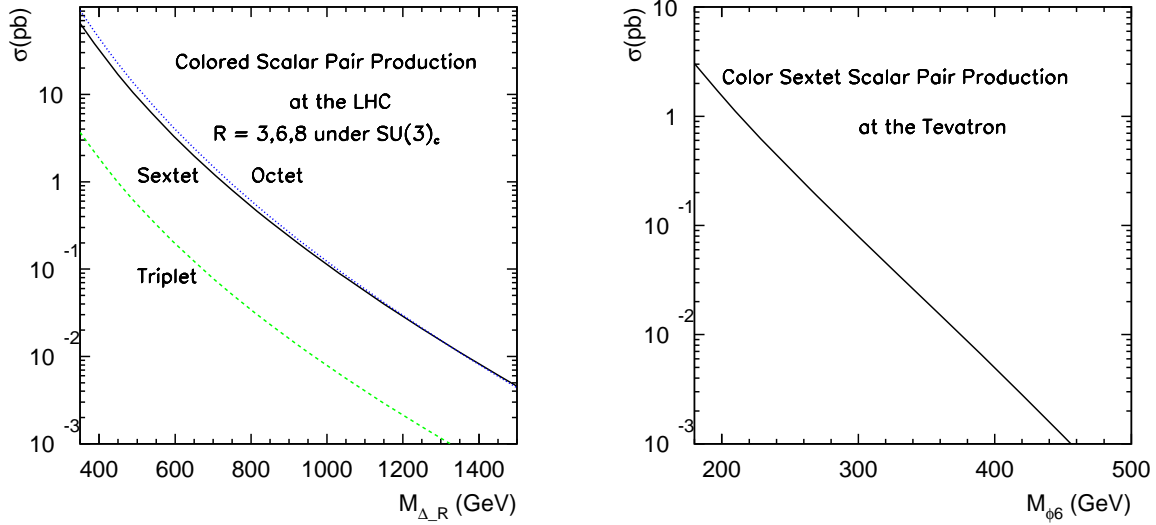
$$uu(cc) \to \Phi_6. \tag{10}$$

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FIG. 2: Production of $\bar{\Phi}_6\Phi_6$ at the LHC and Tevatron with $\mu_F = M_{\Phi_6}$, fixed scale $\alpha_S(\mu_R)$ with $\mu_R = m_Z$. The PDF set CTEQ6L has been used in all calculation.

However, the production cross section is proportional to the coupling $|f_{uu}|^2$ and $|f_{cc}|^2$, and may therefore be suppressed due to the $D^0 - \bar{D}^0$ mixing constraint. Some studies of the single Φ_6 production at the Tevatron and the LHC have been done in Ref. [5].

IV.   SEARCHING FOR THE COLOR SEXTET SCALAR THROUGH $t\bar{t}t\bar{t}$

As discussed in the previous sections, the most distinct feature of the color sextet scalar is its decay mode $\Phi_6 \to tt$, which leads to a same-sign dilepton signature in the final state if both top quarks decay semileptonically, i.e. $t \to W^+b \to \ell^+\nu b$. To avoid ambiguities in lepton assignments during reconstruction, we require the anti-top quark pair from the $\bar{\Phi}_6$ to decay hadronically. Hence, the final state of $\bar{\Phi}_6\Phi_6$ is

$$pp \to \bar{\Phi}_6\Phi_6 \to tt\bar{t}\bar{t} \to 4b + \ell^\pm\ell^\pm + \not{E}_T + Nj, \tag{11}$$

where $\ell = e$ and μ and $N \geq 4$ to allow initial and final state QCD radiation. In our study, however, the QCD radiation is not included. To get this final state, the decay branching ratio will be

$$\text{BR} = \text{BR}^2(\Phi_6 \to tt) \times \left(\frac{2}{9}\right)^2 \times \left(\frac{2}{3}\right)^2 \times 2, \tag{12}$$

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where the situation that top quark decays hadronically and anti-top quark decays semileptonically is also included. Figure 2 also clearly shows that a color sextet with $M_{\Phi_6} \geq 350$ GeV will not be bounded by Tevatron data as the same-sign dilepton plus multi-jet final state from $tt\bar{t}t$ will be less than one event for 2 fb^{-1} luminosity.

To illustrate the kinematic features of the color sextet scalar pair, we consider the decay process $\Phi_6\bar{\Phi}_6 \rightarrow tt\bar{t}\bar{t} \rightarrow b\bar{b}b\bar{b}\ell^+\ell'^+ + 4jets$ and take $M_{\Phi_6} = 600$ GeV. The leading and second-leading jet p_T distributions are shown in Fig. 3. The typical hardness of these jets is the basis for one of our selection cuts introduced later in this section. In order simulate the detector effects on the energy-momentum measurements, we smear the electromagnetic energy and the muon momentum by a Gaussian distribution whose width is parameterized as [13]

$$\frac{\Delta E}{E} = \frac{a_{cal}}{\sqrt{E/\text{GeV}}} \oplus b_{cal}, \quad a_{cal} = 5\%, b_{cal} = 0.55\%, \tag{13}$$

$$\frac{\Delta p_T}{p_T} = \frac{a_{track}p_T}{\text{TeV}} \oplus \frac{b_{track}}{\sqrt{\sin\theta}}, \quad a_{track} = 15\%, b_{track} = 0.5\%. \tag{14}$$

The jet energies are also smeared using the same Gaussian formula as in Eq. (13), but with [13]

$$a_{cal} = 100\%, \quad b_{cal} = 5\%. \tag{15}$$

We first reconstruct the two on-shell hadronically decaying W's. Our procedure is to consider all dijet invariant masses except for those containing one of the two tagged b-jets, since we require b-tagging in the event selection discussed later, and choose the two closest M_{jj} combinations, which we then require to lie within the mass window

$$|M_{jj} - m_W| < 15\text{GeV}. \tag{16}$$

From this, we get the two reconstructed W momenta. We then consider all combinations of reconstructed p_W with all jets and again choose the two closest invariant masses M_{jW}. In this way, we reconstruct the two hadronically decaying anti-top quarks. The distributions of these reconstructed invariant masses are shown in Fig. 4.

Once we have the reconstructed two anti-top quarks, the reconstruction of the sextet ($\bar{\Phi}$) can be done using the 6-jet invariant mass M_{6j} for the two hadronic anti-top quarks. Although the production of neutrinos prevents us from fully reconstructing the sextet which
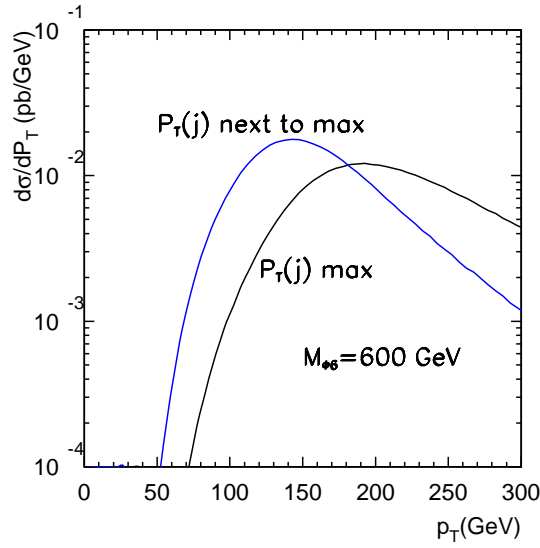
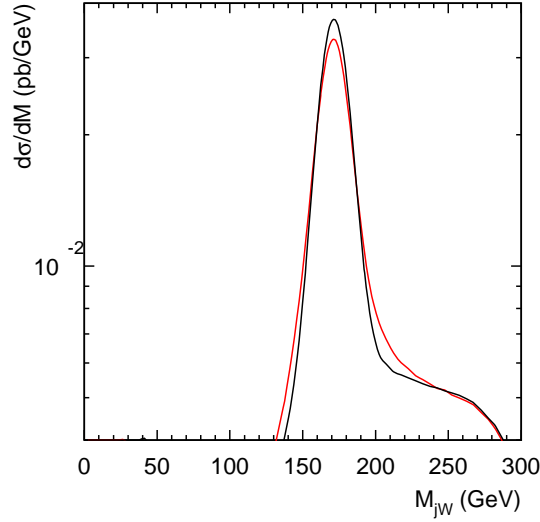FIG. 3: $\max\{p_T^J\}$ and next-to-max$\{p_T^J\}$

FIG. 4: Reconstructed Hadronic Top Pair. The black(red) line represents the first(second) reconstructed hadronically decaying anti-top quark.

produces the leptonic decays, we may reconstruct the transverse mass M_T for the remaining two jets plus same-sign dilepton and $\not{E}_T$ as

$$M_T = \sqrt{\left(\sum_j E_T + \sum_\ell E_T + \not{E}_T\right)^2 - \left(\sum \vec{p}(j) + \sum \vec{p}(\ell) + \not{\vec{p}}\right)_T^2}. \qquad (17)$$
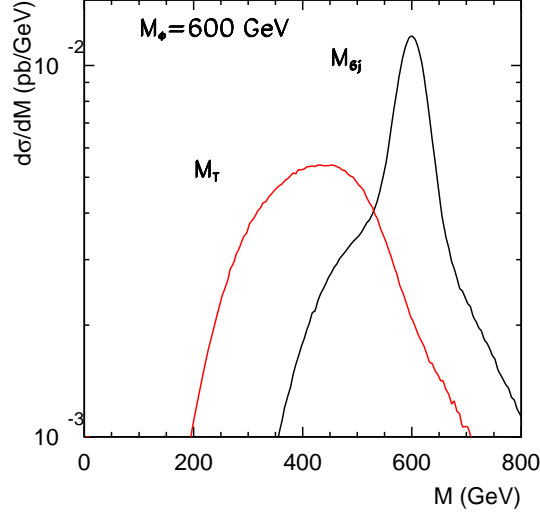
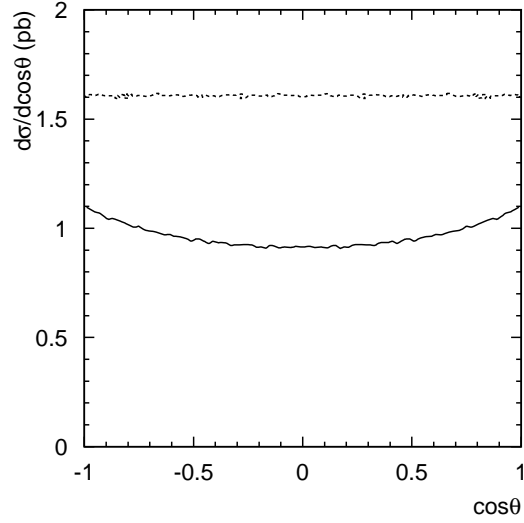FIG. 5: Reconstructed Sextet from m_{6j} and M_T.

FIG. 6: Distribution of $\cos\theta$ between reconstructed top momentum and reconstructed sextet momentum. Dashed(Solid) line shows the distribution without(with) smearing effects and kinematic cuts.

As seen in Fig. 5, our reconstruction shows a clear resonance in both the M_{6j} and M_T distributions.

Finally, since the two anti-top quarks may be fully reconstructed, we can boost back to

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the rest frame of the $\bar{\Phi}_6$ and study its spin. As shown in Fig. 6, the angular distribution of the anti-quark clearly shows that the $\bar{\Phi}_6$ is a scalar. Since there are two missing neutrinos from decay of two top quarks, it is challenging to fully reconstruct top quark's momentum, and study the spin information of top quarks, which can be used to check this model since Φ_6 only decays into a right-handed top quark pair. We leave this for future work.

We next consider the backgrounds for our signal. We require at least 2 tagged b-jets plus a same-sign dilepton and multijet. The irreducible SM background for this final state consists of $t\bar{t}W^{\pm} + Nj$, $bb + W^{\pm}W^{\pm} + Nj$ and $t\bar{t}t\bar{t}$. We estimate the QCD $bb + W^{\pm}W^{\pm} + Nj$ background by computing $jjW^{\pm}W^{\pm}$ production. This is only 14 fb, and one expects the $bb + W^{\pm}W^{\pm} + Nj$ is about three orders lower and therefore < 0.1 fb. The SM 4-top $t\bar{t}t\bar{t}$ is less than 0.1 fb to start with. The leading background thus comes from $t\bar{t}W^{\pm}$ with one hadronic top decay and one semileptonic top decay with the same sign as $W^{\pm}$ leptonic decay.

We propose the following selection cuts:

- $\min\{p_T(j)\} > 15$ GeV, $\max\{p_T(j)\} > 100$ GeV, next-to-max$\{p_T(j)\} > 75$ GeV, $|\eta(j) < 3.0|$

- same sign dilepton with $p_T(\ell) > 15$ GeV, $|\eta(\ell) < 2.8|$

- ΔR_{jj}, ΔR_{jl}, $\Delta R_{ll} > 0.4$

- at least two b-tagged jets

- $\not{E}_T > 25$ GeV

Since the production rate of our signal only depends on the mass M_{Φ_6} and branching ratio of Φ_6 decay to a top quark pair, we scan these two parameters to study the discovery potential. We summarize our results in Fig. 7 as the signal production rate for $bb\bar{b}\bar{b} + \ell^{\pm}\ell^{\pm} + \not{E}_T + 4j$ from $\Phi_6\bar{\Phi}_6$ with SM $t\bar{t}W^{\pm}$ background included. We use a factor of 25% in both plots in Fig. 7 for tagging two b jets with 50% effeciency to tag each b-jet. The SM background is taken as 1 fb in the significance contour. As we can see in the left plot of Fig. 7, for 100 fb^{-1} luminosity, the statistical significance can surpass the 5σ level for $M_{\Phi_6} \lesssim 800$ GeV if BR($\Phi \to tt$) is about 0.5. Also note that the mass of the sextet scalar can be determined by reconstructing two hadronically decaying top (or anti-top) quarks, and the branching ratio of $\Phi_6 \to tt$ can be roughly estimated from the total signal event rate
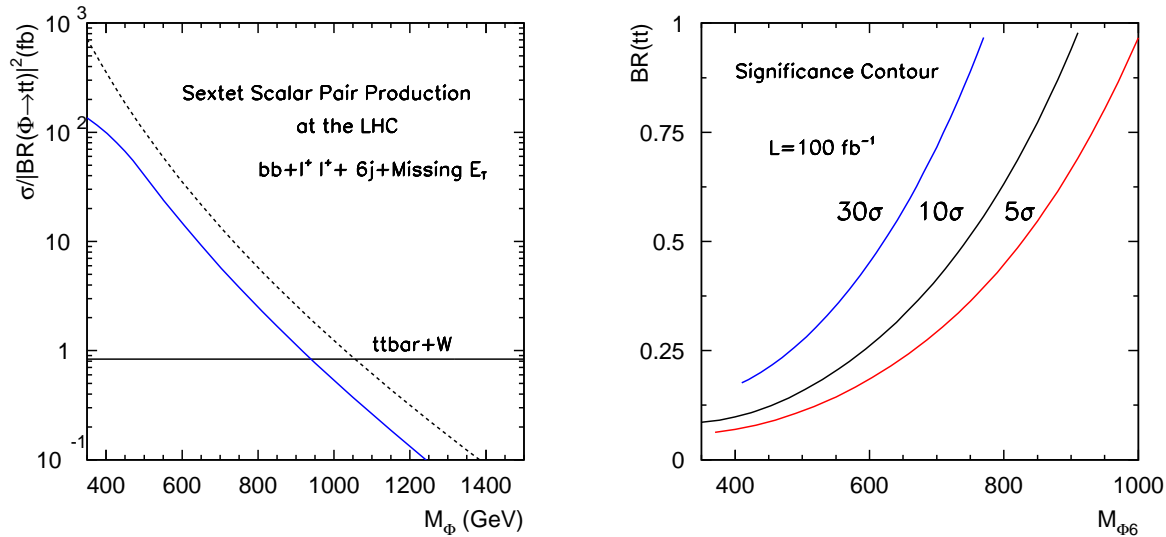
FIG. 7: Production Rate normalized by $BR(\Phi_6 \to tt)^2$ and Significance Contour. Dashed(solid) curves in left plot represent production before(after) selection cuts.

if the one can understand the backgorund sufficiently well. No reconstruction selection has been implented since we did not simulate the events with initial state/final state radiation and the reconstruction efficiency is thus unknown. In principle, we expect that the $S/\sqrt{B}$ can be further improved by including reconstruction.

V. CONCLUSION

In this paper, we discuss the production of a new exotic particle, a color sextet scalar, at the CERN Large Hadron Collider. Taking a purely phemenological approach, we discuss the discovery of the color sextet scalar through its decay into a top-top quark pair. The unique feature of same sign dilepton plus multijet makes it easy to identify and reconstruct the color sextet scalar object. Due to its large QCD production, it is possible to cover the color sextet scalar up to a mass range of 1 TeV for 100 fb^{-1} integrated luminosity.

In the text, we only consider the case of $M_{\Phi_6} > 2m_t$, where Φ_6 decays into two on-shell top quarks. In the case $2M_{\Phi_6} < m_Z$, there is a possiblity of a Z decaying into a sextet pair, since Φ_6 carries a $U(1)_Y$ charge, which we expect is highly constrained by LEP data. We also expect to find strong constraints from Tevatron data. For example, for M_{Φ_6} just above

$m_t + m_b$ threshold, the $\bar{\Phi}_6 \Phi_6$ signal will directly contribute to $t\bar{t}X$ sample as the offshell top decay products are soft.

Acknowledgement

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